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Fault-tolerant Control of Floating Offshore Wind Turbine's Pitch System Under Actuation Faults

Lei Wang* , Lei Zhang

College of Automation, Chongqing University, Chongqing, 400044, PR China

*Correspondence: leiwang08@cqu.edu.cn

ABSTRACT

The wind power industry has boomed in the decades and offshore wind energy has been growing rapidly in the recent year. However, the significant O&M cost became one of the factors hindering the development of floating WT. From the perspective of entrepreneurs, there exists a tradeoff between keeping the O&M costs at a low level and keeping the WT in normal operation.

The pitch system is a key subsystem of the WT and the pitch system failures increase the O&M costs dramatically. Driven by this, this paper investigated a FTC strategy to maintain nominal pitching performance by tracking the demanded pitch angle in the presence of actuator faults. The proposed method effectively handling the unknown actuator faults, modeling uncertainties, and external disturbance with no need for the fault detection and diagnosis process. The tracking error of the pitch angle is ensured to converge to an adjustable residual set within prescribed finite time at a user pre-assignable decay rate. Simulation results show that the proposed scheme yielded a favorable fault-tolerant tracking performance.

Keywords: Offshore floating wind turbine, Pitch System, Fault-tolerant control.

NOMENCLATURE

Abbreviations	
WT/WTs	Wind turbine /Wind Turbines
FTC	*Fault-tolerant control*
O&M	Operation and Maintenance
PID	Proportional Integration Differential
FDD	Fault Detection and Diagnosis
PLOE	Partial loss of effectiveness
GUUB	Globally uniformly ultimately bounded

1. INTRODUCTION

Offshore floating WT with a greater scale compared to the onshore or bottom-fixed one, remains a promising potentiality for development [1]. For a large-scale floating wind turbine, typically, it requires that output power be regulated as rated one, and unbalance loads on WT be mitigated. To achieve that, the pitch system and pitch angle adjustment mechanisms offer an effective solution [2].

The Pitch system plays a critical role among the subsystems of WT. When the WT operating above rated wind speed, the pitch system is controlled to mitigate loads and produce a rated power output. However, practically the large offshore WTs operate in a harsh environment and encounter unknown loads. The occurrence of faults in the subsystem is inevitable during the long term power generating process, which causes degradation of reliability in power generation and also, more maintenance cost due to increased downtime. According to [3], during the lifetime of a floating offshore wind turbine, the cost of O&M making up 31.3% of the whole project. During the long-term operation, the pitch system easily suffers from actuator faults that may be induced by the hydraulic system oil leakage or stuck. Under such circumstances, the pitch angle cannot effectively adjust to the desired one, which may do negative effects on the safety and power output of the WT. According to [4], the pitch system accounted for the highest percentage of failures in WTs at over 21%.

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Besides, pitch system failures accounted for 23% of all the downtime in WTs. Therefore, it is extremely essential to ensure the reliability of the pitch system when faults occur to decrease the O&M cost and support reliable wind power generation.

Fault-tolerant control (FTC) has been identified as an effective way to guarantee WT system reliability and performance despite the presence of faults. [5-6]. The unplanned maintenance need and downtime decreased, and the reliability of power generation will be improved under FTC [7]. Over the last decade, the FTC designs for wind turbines have been significantly developed. Typically, the FTC scheme developed for the pitch system is based on Fault Detection and Diagnosis (FDD) process which is important for fault identification. And based on that the controller reconfiguration (CR) scheme was developed. According to [8], most fault detection based control strategies need timely and accurate fault information, and inaccurate fault information may lead to significant performance degradation. Meanwhile, virtual sensor and observer-based FTC frameworks have been applied in the fault estimation process in the FDD module, but the controller performance is sensitive to the design parameters. In all, most of the FTC schemes are lack simplicity in a control structure and design parameters [9]. Besides, most of the schemes treat the pitch actuator as a linear second-order system or be linearized around some operation points, without the consideration of the nonlinear dynamic characteristic on the actuator while the nonlinear nature of the WT raises a critical issue in fault-tolerant control.

The controller is in the form of PID, which is easy to implement and only a few parameters need to select. The transient performance is ensured with the proposed PID control scheme despite the system nonlinearities, parameter changes, unknown disturbances, and actuation failure. Moreover, the tracking error can converge to zero within a predefined finite time.

The structure of this paper is formulated as follows. Section 2 describes the nonlinear pitch system model and formulates the problem. Section 3 gives a specific definition of the speed function, then provides the control method and stability analysis. Simulations are performed, and results are discussed in section 4. Finally, conclusions are given in section 5.

2. MODELING OF THE PITCH SYSTEM AND PROBLEM FORMULATION

In a practical situation, there exists a highly nonlinear relationship between the pitch regulation driving force and pitch angle. The moments on the rotor blade in the adjustment need to be considered as completely as possible. The simplified model describing the pitch variation, whether the pitch control system is electrical or hydraulic, is shown in Figure 1. Based on it, a basic differential equation describing the dynamic response process of pitch angle adjustment.

$$(J_{Li}+J_{BLi})\frac{d^2\beta_i}{dt^2}+(\frac{dJ_{LBi}}{dt}+\frac{dJ_{BLi}}{dt}+k_{DBi}+k_{RLi})\frac{d\beta_i}{dt}+(\frac{k_{DBi}}{dt}+\frac{k_{RLi}}{dt})\beta_i+M_{BLi}=M_{DRi} \quad (1)$$

where J_{Li} denotes the moment of inertia of air mass, J_{BLi} denotes the value equivalent to the inertia of masses due to accelerated air; k_{DBi} denotes the damping coefficient, k_{RLi} denotes the friction coefficient for bearings. β_i is the pitch angle for the ith blade $(i=1,2,3)$; M_{Dri} is the drive torque of the pitch actuator for the ith blade $(i=1,2,3)$, representing the control input of the pitch system. $\frac{d\beta_i}{dt}$ and $\frac{d^2\beta_i}{dt^2}$ represents the angular velocity and its derivative for each rotor blade respectively. Moreover, M_{Bi} denotes the load torque of the rotor.

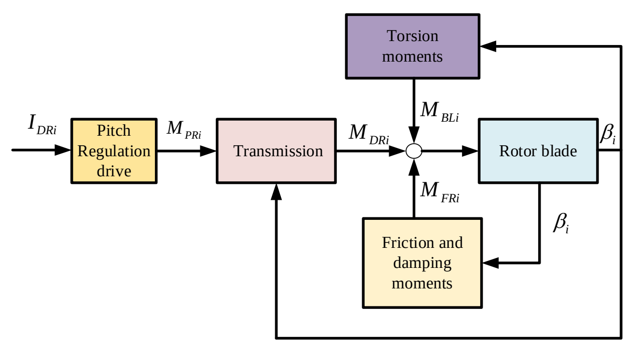

Fig 1 The pitch adjustment mechanism for each rotor blade, adapted from [10]

The pitch system model can be further express as:

$$M(\cdot)\ddot{\beta}+D(\cdot)\dot{\beta}+N(\cdot)\beta+d(\beta,\dot{\beta},t)=u_a \quad (2)$$

where β, u, d, $M(\cdot)$, $D(\cdot)$, $N(\cdot)$ are dialog matrix. And we have

$$\begin{gathered} d_i=M_{BLi} \\ M_i=J_{Li}+J_{BLi}, D_i=\frac{dJ_{LBi}}{dt}+\frac{dJ_{BLi}}{dt}+k_{DBi}+k_{RLi} \\ N_i=\frac{dk_{DBi}}{dt}+\frac{dk_{RLi}}{dt}, u_i=M_{DRi} \end{gathered} \quad (3)$$

As unknown actuation faults are inevitable for long-term operation, the following situation that the pitch actuators are PLOE is considered in this work, which is explicitly considered as part of the system model in conjunction with:

$$u_a = \rho(t)u + \varepsilon(t) \tag{4}$$

where $\varepsilon(t)$ represents the uncontrollable portion of actuation, which may cause the unbalanced rotor rotation, and we have $\|\varepsilon\| \le \bar{\varepsilon} < \infty$. ρ is a diagonal matrix with $\rho_j (j = 1,2,3)$, $0 < \rho_j < 1$ being the "healthy indicator", reflecting the effectiveness of the jth blade pitch actuator.

3. CONTROLLER DESIGN AND STABILITY ANALYSIS

Motivated by [11], a rate function was introduced,

$$\eta(t) = \begin{cases} \dfrac{T^4 k(t)}{\left(1-b_f\right)(T-t)^4 + b_f T^4 k(t)}, & 0 \le t < T \\ \dfrac{1}{b_f}, & t \ge T \end{cases} \tag{5}$$

Where T is a given finite time, and $k(t) = 1 + 2t^2$ is a non-decreasing function. We define the tracking error $e = \beta - \beta^*$. Based on it, a transformed error is introduced as $\xi = \eta e$.

Remark 1: $\eta(t)$ is positive and smooth for all $t \ge 0$, and $\eta(t) \in [1, \frac{1}{b_f}]$ for $t \in [0, +\infty)$.

Remark 2: $\dot{\eta}(t)$ and $\ddot{\eta}(t)$ are continuous and bounded everywhere.

Assumption: The desired pitch angle β^*, along with $\dot{\beta}^*$, $\ddot{\beta}^*$ are known to be smooth function and bounded.

Besides, it holds that $\lambda_m \le \| M(\cdot) \| \le \lambda_M$, $\|\dot{M}(\cdot)\| \le b < \infty$, $D(\cdot) \le k_d$, $N(\cdot) \le k_n$, $d(\cdot) \le b_d$.

The proposed PID control scheme takes the form of

$$u = -\left(k_{D0} + k_D(\cdot)\right)E \tag{6}$$

where E is the generalized error, is defined as

$$E = 2\gamma\xi + \gamma^2 \int_0^t \xi d\tau + \frac{d\xi(\cdot)}{dt} \tag{7}$$

It can be proved that the boundedness of E ensuring the boundedness of z, $\int_0^t z(\cdot)d\tau$, and $\frac{dz(\cdot)}{dt}$. More specifically, the control task boils to design a strategy to determine $k_{D0} > 0$ and $k_D(\cdot)$ automatically and adaptively, such that E is GUUB.

To bridge the generalized error E with the transformed error dynamics we take the time derivative of E to obtain

$$\begin{aligned} \dot{E} &= 2\gamma\dot{\xi}(t) + \gamma^2\xi(t) + \ddot{\xi}(t) \\ &= \eta\ddot{e}(t) + \ddot{\eta}e(t) + 2\dot{\eta}\dot{e}(t) + 2\gamma\dot{\xi}(t) + \gamma^2\xi(t) \\ &= \eta\rho u + \eta\varepsilon - \eta M^{-1}(\cdot)[D(\cdot)\dot{\beta} + \\ &\qquad N(\cdot)\beta + d(\cdot)] + \psi(\cdot) \end{aligned} \tag{8}$$

where $\psi(\cdot) = 2\gamma\dot{\xi}(t) + \gamma^2\xi(t) + \ddot{\eta}e(t) + 2\dot{\eta}\dot{e}(t) - \eta\ddot{\beta}^*$ is a computable function. Multiply both sides of (22) by M, we have

$$\begin{aligned} M\dot{E} &= \eta u - \eta D(\cdot)\dot{\beta} + \eta N(\cdot)\beta + \eta d(\cdot) + M\psi(\cdot) \\ &= \eta(u + l(\cdot)) \end{aligned} \tag{9}$$

where $l(\cdot) = -D(\cdot)\dot{\beta} - N(\cdot)\beta - d(\cdot) + \eta^{-1}M\psi(\cdot)$.

Following the basic properties of the norm and we obtain that

$$\|l(\cdot)\| \le a_f \varphi_f \tag{10}$$

where $\varphi_f = \|\dot{\beta}\| + \|\beta\| + \eta^{-1}[(2\gamma+1)\|\dot{\beta}\| + (\gamma^2+1)\|\beta\|] + 1$ is a computable scalar function, $a_f = \max\{\|D\|, \|N\|, \|M\|, \|d\|\}$.

Based on that, we further define a new variable

$$H(\cdot) = l(\cdot) + \frac{1}{2}\eta^{-1}E\dot{M} \tag{11}$$

Then, we have

$$\begin{aligned} \| H \| &\le \| l(\cdot) \| + \frac{1}{2}\|\eta^{-1}E\| \| \dot{M} \| \\ &\le a_f\varphi(\cdot) + \frac{b}{2}\|\eta^{-1}E\| = a\varphi(\cdot) \end{aligned} \tag{12}$$

where $a = \max\{a_f, \frac{b}{2}\}$; $\varphi(\cdot) = \varphi_f + \|\eta^{-1}E\|$ is a scalar and readily function which can be used for control design, also called "core function".

We employ the PID controller as given in (6) with

$$k_D(\cdot) = \sigma_1\hat{a}\eta\varphi^2(\cdot) \tag{13}$$

and the updated law $\dot{\hat{a}}$ is given by

$$\dot{\hat{a}} = -\sigma_0\hat{a} + \sigma_1\eta\varphi^2(\cdot)\|E\|^2 \tag{14}$$

where σ_0 and σ_1 are some positive design constants, and $\hat{a}$ is the estimation of a.

The following Lyapunov function candidate is obtained as:

$$V = \frac{1}{2}E^T M E + \frac{1}{2\sigma_1}\tilde{a}^2 \tag{15}$$

Note that $\tilde{a} = a - \hat{a}$, where $\hat{a}$ is the estimation of the unknown weight a. The derivative of V can be expressed as:

$$\dot{V} = E^T M\dot{E} + \frac{1}{2}E^T \dot{M}E + \frac{1}{\sigma_1}\tilde{a}\dot{\tilde{a}} \\ = E^T \eta(u + H(\cdot)) - \frac{1}{\sigma_1}a\dot{\hat{a}} \tag{16}$$

We have

$$\dot{V} \le E^T \eta u + \| E\| \ \eta a\varphi(\cdot) - \frac{1}{\sigma_1}\tilde{a}\dot{\hat{a}} \\ \le -E^T \eta\left(k_{D0} + k_D(\cdot)\right)E + \| E\| \ \eta a\varphi(\cdot) - \frac{1}{\sigma_1}\tilde{a}\dot{\hat{a}} \tag{17}$$

By using the facts that $a\eta\varphi(\cdot)\|E\| \le a\eta^2\varphi^2(\cdot)\|E\|^2 + \frac{a}{4}$ and $\frac{\sigma_0}{\sigma_1}\tilde{a}\hat{a} \le \frac{\sigma_0}{2\sigma_1}a^2 - \frac{\sigma_0}{2\sigma_1}\tilde{a}^2$, V can be further bounded as

$$V \le -k_{D0}\eta\| E\|^2 + \eta^2\| E\|^2\varphi^2(\cdot)(a-\hat{a}) \\ + \tilde{a}\eta^2\| E\|^2\varphi^2(\cdot) + \frac{\sigma_0}{2\sigma_1}a^2 - \frac{\sigma_0}{2\sigma_1}\tilde{a}^2 + \frac{a}{4} \\ \le -k_{D0}\eta\| E\|^2 + \frac{\sigma_0}{2\sigma_1}a^2 - \frac{\sigma_0}{2\sigma_1}\tilde{a}^2 + \frac{a}{4} \tag{18}$$

Note that $\eta \ge 1$, we get

$$\dot{V} \ \le -k_{D0}\| E\|^2 - \frac{\sigma_0}{2\sigma_1}\tilde{a}^2 + \frac{\sigma_0}{2\sigma_1}a^2 + \frac{a}{4} \le -cV + \Theta \tag{19}$$

where $c = \min\{\frac{2k_{D0}}{\lambda_M}, \sigma_0\}$, $\Theta = \frac{\sigma_0}{2\sigma_1}a^2 + \frac{a}{4}$ .So the stability is proved, all the signals in the closed-up systems are bounded. Furthermore, by solving each component of E in (7), we have:

$$|e_i| \le \begin{cases} \left(1-b_f\right)\left(\frac{T-t}{T}\right)^4 k^{-1}B_{\varepsilon_i} + b_f\varepsilon_{i,} & 0 \le t < T \\ b_f\left|\varepsilon_i\right|, & t \ge T \end{cases} \tag{20}$$

Where B_{ε_i} is a bounded compact set. Noting that the tracking error e converges to residual set within finite time T at the preassigned decay rate, which can be adjusted by b_f .

Remark 3:

When under the situation of $b_f = 1$, which means $\eta = 1$, one can get the following control scheme:

We call the above control scheme (23) -(24) the normal nonlinear adaptive PID control.

4. SIMULATION AND RESULTS

In this section, to verify the effectiveness of the proposed PID FTC scheme, numerical simulations are carried on NREL's 5 MW Spar type WT model. The three desired pitch angles, wind speed with an effective speed of 18m/s are as shown in Fig.2.

The components of the dynamic equation for the pitch system are given as follows:

$$M(\cdot) = diag(\sin(\beta_1 t)+3, \sin(\beta_2 t)+3, \\ \sin(\beta_2 t)+3) \tag{27}$$

$$N(\cdot) = diag(\sin(\beta_2 t)+\sin(\dot{\beta}_2)+2, \ \sin(\beta_2 t)+ \\ \sin(\dot{\beta}_2)+2, \sin(\beta_2 t)+\sin(\dot{\beta}_2)+2) \tag{28}$$

$$D(\cdot) = diag(\cos(\beta_1 t+\dot{\beta}_1)+2, \cos(\beta_2 t+\dot{\beta}_2)+2, \\ \cos(\beta_3 t+\dot{\beta}_3)+2) \tag{29}$$

$$d(\cdot) = \begin{bmatrix} 0.5\cos(\beta_1 t)+3\sin(0.5\dot{\beta}_1 t)+\xi_1 \\ 0.5\cos(\beta_2 t)+3\sin(0.5\dot{\beta}_2 t)+\xi_2 \\ 0.5\cos(\beta_3 t)+3\sin(0.5\dot{\beta}_3 t)+\xi_3 \end{bmatrix} \tag{30}$$

The initial pitch angles of 3 rotor blades are given as $\beta_1(0) = \beta_2(0) = \beta_3(0) = 3^\circ$. For simplicity, a scenario that only blade 1 suffered from the actuation failure was considered. The health indicator and the additive faults of floating WT's pitch system are chosen as

$$\rho_1 = \begin{cases} 1 & 0 \le t \le 100 \\ 0.7 + 0.3\sin(0.01\pi * t) & 100 < t \le 200 \end{cases} \tag{31}$$

$$\rho_2 = \rho_3 = 1 \tag{32}$$

$$[\varepsilon_1, \varepsilon_2, \varepsilon_3]^T = [\sin(\beta_1), 0, 0]^T \tag{33}$$

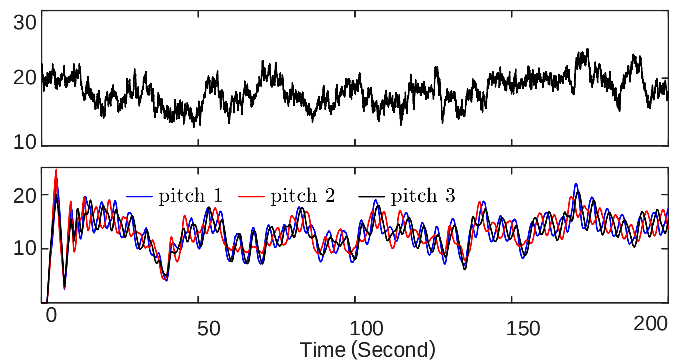

Fig 2 Turbulent wind speed with a mean of 18m/s and desired pitch angle

In the simulation, two cases are considered to clearly verify the reliable and effective tracking performance realized by the proposed FTC scheme.

Case 1: Tracking a random signal under different settling time T .

In this case, to demonstrate that the proposed method can achieve zero error tracking within a different predefined time($T = 4,8$), we assume that the desired pitch angle as $\beta^* = 2 + \sin(0.5t)$. Meanwhile, the parameters of the controller are chosen as $k_{D0} = 20$, $\gamma = 1.2$, $\sigma_0 = 0.5$, $\sigma_1 = 0.001$, $b_f = 0.1$ .The results are shown in Fig.3 and Fig.4, Fig.3 is the pitch tracking error and the control input of blade 1 under different user-defined time. Fig.4 shows the control input. It can be seen that the tracking error e can converge to a residual set within a finite time T, which is preassigned by the user. Moreover, the controller can achieve better transient performance by reducing T properly.

Case 2: Tracking the desired pitch angle under different b_f. different b_f. We set the fixed time $T=8$ s and speed function $\kappa = 1+2t^2$, the design parameter b_f is chosen as 0.1 and 1, respectively.

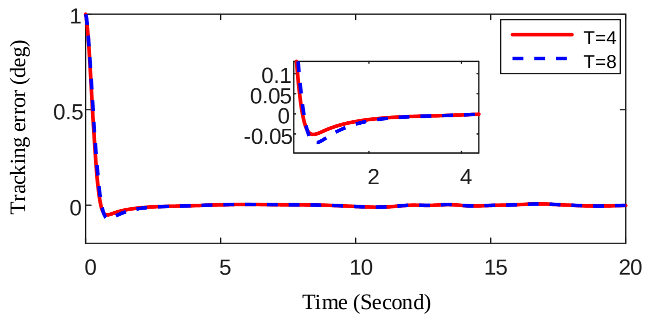

Fig 3 Tracking error under different settling time

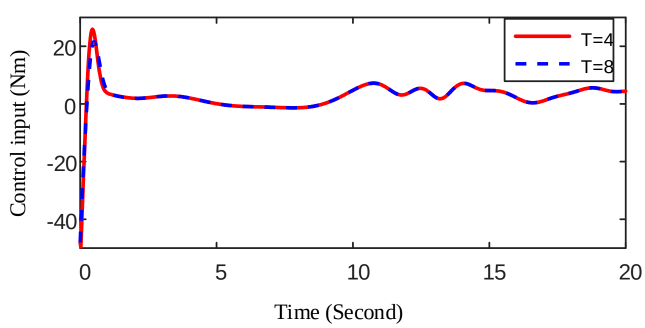

Fig 4 Control input under different settling time

It is noted that when $b_f = 1$ the proposed FTC controller became a normal PID adaptive FTC method. The parameters of the FTC controller in the simulation are chosen as $k_{D0} = 50$, $\gamma = 1.2$, $\sigma_0 = 0.5$, $\sigma_1 = 0.001$. The results are shown in Figure 5 and Figure 6, where Fig.5 shows the tracking error of the proposed accelerated FTC scheme, and Fig.6 shows the tracking error under normal control method. From the simulation results, we can clearly see that both two control schemes exhibited admirable fault-tolerant capacity when faults happened. Moreover, the former one can realize a stable and steady performance, thus ensure the tracking error converges to 0.

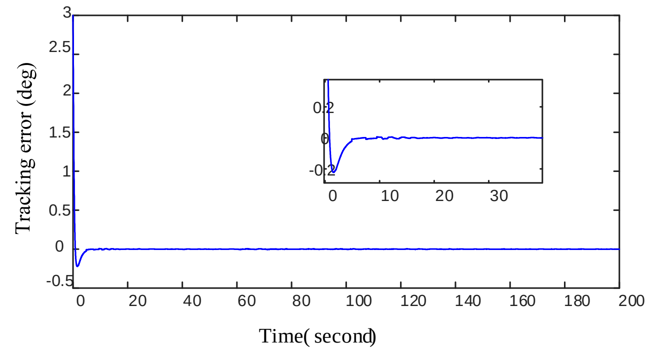

Fig 5 The tracking error of pitch angle 1 under the proposed accelerated control scheme

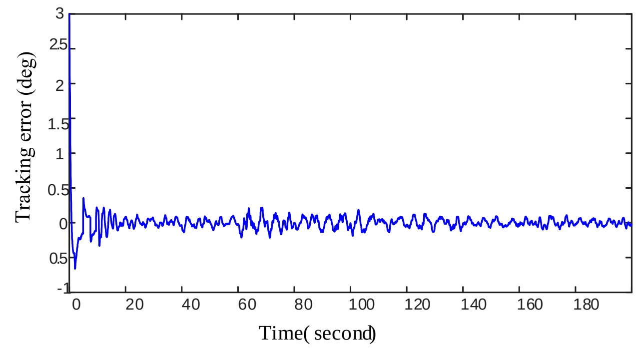

Fig 6 The tracking error of rotor blade 1 under the normal control scheme

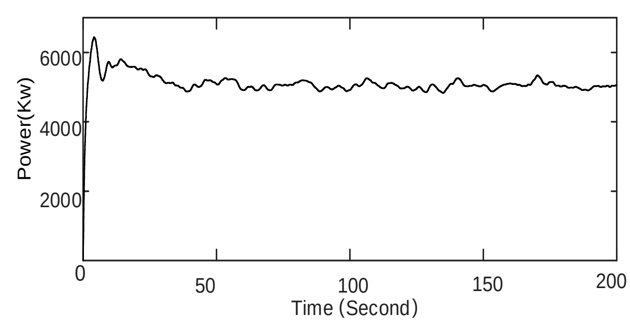

Fig 7 The tracking error of pitch angle 1 under the proposed accelerated control scheme

Finally, this paper analyses the power output of the WT under actuation failure, as shown in Figure 7. From which we verify that the proposed method can achieve a stable power generation when actuator faults happened.

5. CONCLUSIONS

An adaptive FTC scheme was proposed for the nonlinear WT's pitch system to maintain nominal pitching performance and compensate for unknown pitch actuator faults. The proposed method corrects the PID gains automatically, which is more user friendly in control design, and easier for real-time implementation.

Moreover, the specific parameter of the system and the actuation failure are not required in the controller design, which means the FTC scheme does not require a FDD process. Besides, the presented FTC scheme can guarantee a favorable transient performance, and the tracking error is ensured to converge to a small residual set within finite time. On this basis, one can conclude that the proposed FTC method is able to recover the nominal pitch actuation, thus ensure a stable power output in given finite time under the actuator faults and external disturbance.

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